

Galaxy merger histories and the role of merging in driving star formation at $z > 1$

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ABSTRACT

We use Horizon-AGN, a hydrodynamical cosmological simulation, to explore the role of mergers in the evolution of massive ($M_* > 10^{10} M_\odot$) galaxies around the epoch of peak cosmic star formation ($1 < z < 4$). The fraction of massive galaxies in major mergers (mass ratio $R < 4 : 1$) is around 3%, a factor of ~ 2.5 lower than minor mergers ($4 : 1 < R < 10 : 1$) at these epochs, with no trend with redshift. At $z \sim 1$, around a third of massive galaxies have undergone a major merger, while all such systems have undergone either a major or minor merger. While almost all major mergers at $z > 3$ are ‘blue’ (i.e. have significant associated star formation), the proportion of ‘red’ mergers increases rapidly at $z < 2$, with most merging systems at $z \sim 1.5$ producing remnants that are red in rest-frame UV-optical colours. The star formation enhancement during major mergers is mild (~ 20 – 40%) which, together with the low incidence of such events, implies that this process is not a significant driver of early stellar mass growth. Mergers ($R < 10 : 1$) host around a quarter of the total star formation budget in this redshift range, with major mergers hosting around two-thirds of this contribution. Notwithstanding their central importance to the standard Λ CDM paradigm, mergers are minority players in driving star formation at the epochs where the bulk of today’s stellar mass was formed.

Key words: galaxies: formation – galaxies: evolution – galaxies: interactions – galaxies: high-redshift

1 INTRODUCTION

The cosmic star formation history indicates that the bulk of the stars in today’s massive galaxies formed at $z \sim 2$ (e.g. Madau et al. 1998; Hopkins & Beacom 2006). While the nearby Universe underpins much of our current understanding of galaxy evolution, a convergence of new multi-wavelength surveys (e.g. Windhorst et al. 2011; Grogin et al. 2011) and high-resolution hydrodynamical simulations (e.g. Devriendt et al. 2010; Dubois et al. 2014; Schaye et al. 2014; Khandai et al. 2014; Vogelsberger et al. 2014) is revolutionizing our understanding of the $z > 1$ Universe. The processes that drive galaxy growth at these early epochs are still the subject of much debate. The role of mergers (major mergers in particular) at high redshift remains poorly understood. While mergers are capable of inducing strong star formation, black-hole growth and morphological

transformations (e.g. Springel et al. 2005), both theory (e.g. Kereš et al. 2009; Dekel et al. 2009) and observation (e.g. Genzel et al. 2011; Kaviraj et al. 2013a, K13a hereafter) have recently suggested a lesser (perhaps insignificant) role for this process in driving stellar mass growth in the early Universe.

Spectroscopic studies of star-forming galaxies around $z \sim 2$ have demonstrated high fractions of systems that are not in mergers but show kinematic morphologies indicative of turbulent discs (e.g. Förster Schreiber et al. 2006; Genzel et al. 2008; Shapiro et al. 2008; Law et al. 2009; Mancini et al. 2011). Since galaxy morphology carries an imprint of the mechanisms that drive star formation (e.g. Lintott et al. 2011), imaging studies, using e.g. high-resolution instruments like the *Hubble Space Telescope*, have offered a complementary route to probing the processes that dominate stellar mass growth at $z > 1$. In broad agreement with the spectroscopic literature, a possible dominance of non-merging galaxies within the early star-forming popula-

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tion has been suggested by such work (e.g. Lotz et al. 2006; Förster Schreiber et al. 2011; Law et al. 2012; Kaviraj et al. 2013a). In particular, Kaviraj et al. (2013a; K13a hereafter) have probed the overall significance of (major) merger-driven star formation in the early Universe, by estimating the fractional contribution of visually-classified mergers to the star formation budget at $z \sim 2$. Their work estimates that less than a third of the budget at this redshift is hosted by systems that are in major mergers.

While observational studies are transforming our understanding of the role of mergers at $z > 1$, the empirical literature unavoidably uses a heterogeneous set of methodologies and is often restricted to relatively small galaxy samples, with each study typically probing a relatively narrow range in redshift. A complementary approach to exploring the role of merging is to use a theoretical model that is well-calibrated to the observed Universe at these epochs. In this study, we exploit Horizon-AGN, a hydrodynamical cosmological simulation that reproduces the mass functions and rest-frame UV-optical colours of massive galaxies at $z > 1$, to probe the impact of merging on massive ($M_* > 10^{10} M_\odot$) galaxies at $1 < z < 4$. Our principal objectives are to perform a statistical study of major/minor merger histories, the enhancement of star formation in major mergers and the proportion of the star formation budget that is attributable to mergers around the epoch of peak star formation.

This Letter is organized as follows. In Section 2, we describe the simulation that underpins our study. In Section 3, we study the fractions of galaxies in major and minor mergers at $1 < z < 4$, the cumulative merger histories of massive galaxies at $z \sim 1$ and the star formation activity in mergers across this epoch. In Section 4, we study the enhancement of star formation induced by the major-merger process and calculate the fraction of the star formation budget that is hosted by merging systems at these redshifts. We summarize our findings in Section 5.

2 THE HORIZON-AGN SIMULATION

We begin by summarizing the main properties of the Horizon-AGN simulation - we refer readers to Dubois et al. (2014) for further details. The simulation employs the adaptive mesh refinement Eulerian hydrodynamics code, RAMSES (Teyssier 2002). The size of the simulated volume is $100 h^{-1} \text{Mpc}$ comoving, containing 1024^3 dark matter particles with initial conditions that correspond to a standard ΛCDM cosmology with Planck-like values (Planck Collaboration et al. 2013). The initial 1024^3 uniform grid is refined with a quasi Lagrangian criterion when 8 times the initial total matter resolution is reached in a cell, down to a minimum cell size of 1 kpc in proper units.

Metal-dependent radiative cooling is implemented following Sutherland & Dopita (1993) and a uniform UV background is switched on at $z = 10$, following Haardt & Madau (1996). The standard Schmidt-Kennicutt law (e.g. Kennicutt 1998) is employed to produce star particles with a 2% efficiency, when the gas density reaches a critical density of 0.1 H cm^3 . Based on Dubois & Teyssier (2008), mass loss from massive stars occurs via stellar winds and Type II and Type Ia supernovae, which disperse gas and metals into the ambient medium (Kimm et al, in prep.). Seed

black holes (BHs) with a mass of $10^5 M_\odot$ are assumed to form in regions of high gas density and the growth of the BH is tracked self consistently based on a modified Bondi accretion rate. When gas accretes on to BHs, we assume that a central BH impacts the ambient gas in two possible ways, depending on the accretion rate. For a high accretion rate (Eddington ratio > 0.01), 1.5 per cent of the accretion energy is injected as thermal energy (a quasar-like feedback mode), while jets are employed for low accretion rates (Eddington ratios < 0.01) with a 10 per cent efficiency (Dubois et al. 2012). Due to the presence of AGN feedback, the mass functions of massive galaxies and the rest-frame UV-optical colours of observed galaxies around the epoch of peak cosmic star formation are well reproduced by our model (Kimm et al. 2012; Dubois et al. 2014). Given the high sensitivity of the rest-frame UV wavelengths to star formation (e.g. Martin et al. 2005; Kaviraj et al. 2007), the agreement with UV-optical colours (and mass functions) implies a good reproduction of galaxy star formation histories in the simulation, making it a useful tool for exploring the processes that drive stellar mass growth at these epochs.

We build merger trees using TreeMaker (Tweed et al. 2009), with a typical time difference between time steps of $\sim 35 \text{ Myr}$ (the range is between 20 and 60 Myr). Here, we explore the merger histories of the set of ~ 1100 Horizon-AGN galaxies at $z \sim 1.2$ that have masses greater than $10^{10} M_\odot$. The minimum galaxy mass probed is $\sim 10^{8.5} M_\odot$, making the simulation complete to mergers with mass ratios of $\sim 10 : 1$ or less. Our subsequent analysis is restricted to this range of mass-ratio values. In what follows, mergers are defined as systems that merge within a timescale of $\sim 0.1 \text{ Gyrs}$. These galaxies are at the final stages of a merger, with the centres of the merger progenitors typically less than 20 kpc from each other. Tidal features are more readily observable in images at such separations (e.g. Darg et al. 2010a,b), making our model results better aligned with observations of ‘close pairs’ systems at similar relative distances.

3 MERGER HISTORIES OF MASSIVE GALAXIES

We begin by exploring the merger histories of massive galaxies around the epoch of peak cosmic star formation. In the top panel of Fig. 1, we present the fractions of galaxies in mergers of various mass ratios (R), where R is defined as the mass of the larger progenitor divided by the mass of its smaller counterpart. The fractions of merging systems with $R < 4 : 1$ (‘major’ mergers), $4 : 1 < R < 10 : 1$ (‘minor’ mergers) and $R < 10 : 1$ (major + and minor mergers) are around 3%, 8% and 11% respectively, with no trend with redshift. In the redshift range $1 < z < 4$, the number of minor mergers is around a factor of 2.5 higher than their major counterparts (bottom panel of this figure). In Fig. 2, we present a cumulative view of the average merger history of massive galaxies at $z \sim 1$. We show the fraction of galaxies that have had a merger with a mass ratio less than the value on the x-axis. Thus, by $z \sim 1$, 30% of galaxies have had a major merger, while all massive galaxies have had either a major or minor merger with $R < 10 : 1$. Note that we do not consider mass ratios greater than $10 : 1$ because,

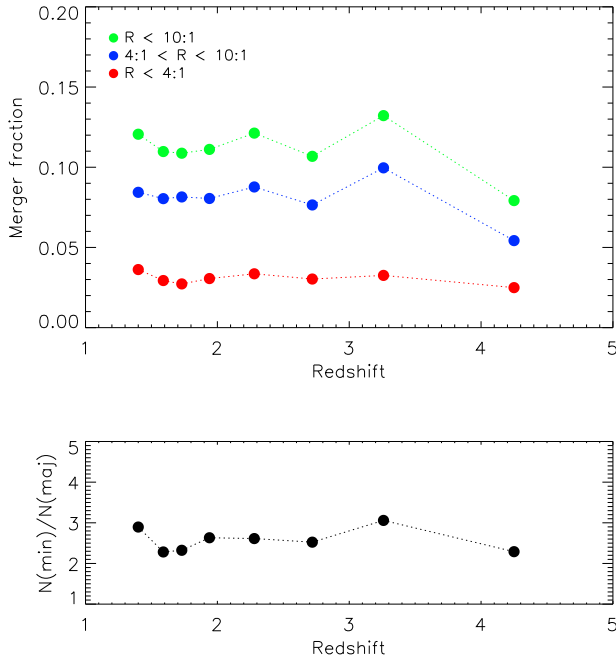


Figure 1. Top: Fractions of massive galaxies in mergers of different mass ratios (R). The red line indicates major mergers ($R < 4:1$), the blue line indicates minor mergers ($4:1 < R < 10:1$), while the green line indicates all mergers with $R < 10:1$. **Bottom:** The ratio of minor to major mergers (i.e. the ratio of the red and blue curves in the panel above).

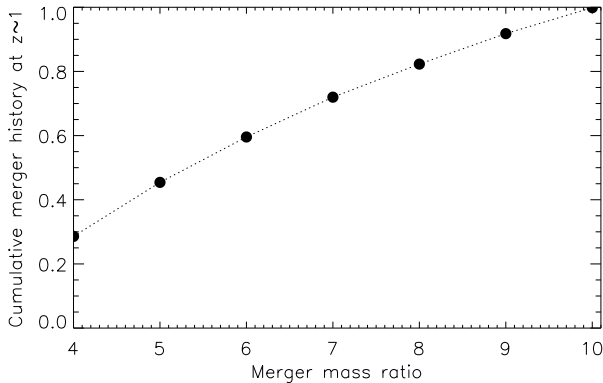


Figure 2. The fraction of massive galaxies at $z \sim 1$ that have had a merger with a mass ratio (R) less than the value on the x-axis. For example, at $z \sim 1$, 30% of galaxies have had a major merger ($R < 4:1$), while all massive galaxies have had either a major or minor merger with ($R < 10:1$).

as noted above, the simulation is incomplete beyond these mass ratios across our redshift range of interests.

The major merger fractions in our model and their lack of redshift evolution are consistent with both Λ CDM values from the Millenium simulation (e.g. Bertone & Conselice 2009) and empirical merger fractions (e.g. Man et al. 2012). The cumulative merger history estimated by observational studies suggests that a massive galaxy experiences ~ 1.1 ma-

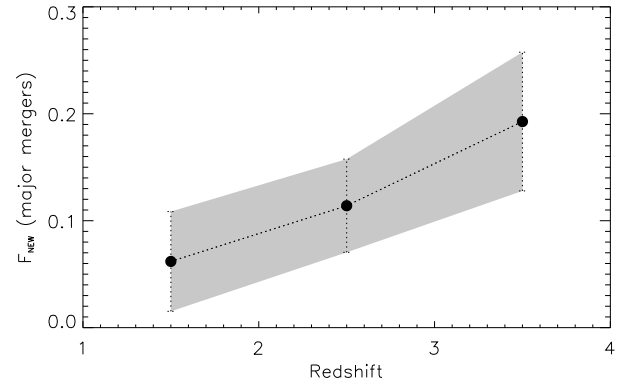


Figure 3. The mass fraction (F_{new}) of young (age < 0.1 Gyr) stars in major-merger remnants. The points indicate median values, while the width of the shaded region indicates the standard deviation in the values of F_{new} at that redshift.

ior mergers in the redshift range $0 < z < 3$ (Man et al. 2012, see also Bluck et al. 2012). Assuming the merger rate does not evolve strongly with redshift, as suggested by this study and others (e.g. Lotz et al. 2011; Man et al. 2012), this indicates that around a third of massive galaxies will have experienced a major merger by $z \sim 1$, in agreement with the cumulative merger histories presented in Fig. 2. Finally, the ratio of minor to major mergers ($\sim \times 2.5$) in our model is also consistent with recent observational work (Lotz et al. 2011; Bluck et al. 2012).

It is worth noting here that the observational literature on mergers is still developing at these epochs, and that the dispersion in current observational estimates of the merger fraction can be significant, with different studies reporting values that are discrepant by several factors (see e.g. the compilation of results in figure 12 of Conselice 2014). The discrepancies are likely to be driven by different selection techniques, low number statistics in the high-redshift fields and cosmic variance (e.g. Lotz et al. 2011). The large current dispersion in the observational data makes a theoretical study such as this one useful, both for providing a quantitative picture of galaxy merging at $z > 1$, and for offering theoretical estimates that can be better tested as the observational literature matures.

In Fig. 3 we study the star formation activity in major mergers. Since the literature often invokes red mergers (i.e. those where the fraction of new stars formed is close to zero) to explain massive-galaxy evolution, it is useful to explore the star formation that is associated with mergers at these epochs. We define the fraction of ‘new’ stars as the fraction of stellar mass formed within the last 0.1 Gyr (F_{new}), which is close to typical dynamical timescales at these epochs (e.g. Ceverino et al. 2010). The points in this figure indicate median values, while the width of the shaded region indicates the standard deviation in the distribution of F_{new} values at a given redshift.

We cast our results in terms of an empirical boundary between ‘red’ and ‘blue’ systems, estimated via recent observational work at these epochs. Using star formation histories constructed via spectral energy distribution (SED) fitting (Kaviraj et al. 2013b, K13b hereafter) have recently

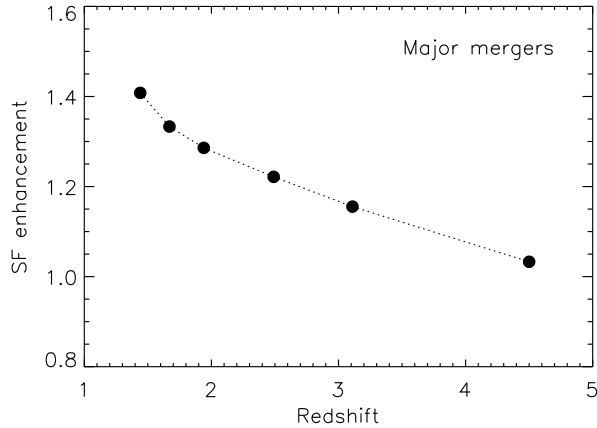


Figure 4. Star formation enhancement in systems that are major mergers. The enhancement is defined as the ratio of the total star formation activity in mergers to that in non-merging systems at a given redshift.

studied the rest-frame UV-optical colours of massive galaxies at $1 < z < 3$. The high sensitivity of the UV wavelengths to star formation means that even small mass fractions of young stars (of the order of a percent or less) will drive galaxies into the UV-optical blue cloud (e.g. Yi et al. 2005; Kaviraj et al. 2007), making the UV-optical colour space particularly effective at separating star-forming and quiescent systems. Taking the boundary between red and blue galaxies to be $(NUV - V) \sim 3$ (see figure 4 in K13b), the SED-fitted star formation histories in K13b indicate that galaxies that are blue in UV-optical colours typically have $F_{new} \gtrsim 0.1$. We therefore take $F_{new} = 0.1$ as the boundary between red and blue systems in our subsequent analysis. Based on the blue vs red threshold assumed above, we find that, while almost all major mergers at $z > 3$ are blue, the proportion of red mergers increases rapidly at $z < 2$. At $z \sim 1.5$, most (but not all) major mergers are red in UV-optical colours (i.e. produce very little star formation).

4 ARE MAJOR MERGERS SIGNIFICANT DRIVERS OF STAR FORMATION?

The overall role of the major-merger process in driving stellar mass growth has been an important question in the recent literature (e.g. K13a; Rodighiero et al. 2011). The overall significance of major-merger driven star formation depends both on the frequency of such mergers and on the enhancement of star formation that is induced when a major merger event takes place. Thus, if the enhancement of star formation is high during the merger, then major-merger-driven star formation can be a significant contributor to the star formation budget, even if the merger fraction itself is relatively low (as has been shown to be the case in the previous section).

In Fig. 4 we present the enhancement of star formation during major mergers. The enhancement is defined as the average F_{new} in merging systems divided by the average F_{new} in the population of galaxies that are not undergoing a major merger. We find that the enhancement is relatively

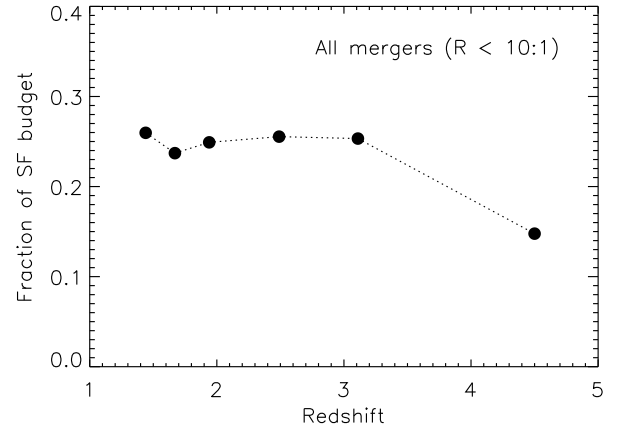


Figure 5. The fraction of the total star formation budget that is hosted by systems that are in mergers with $R < 10 : 1$. Major mergers host around two-thirds of the contribution, without much trend with redshift.

mild - around 20-40% in the redshift range $1 < z < 3$. This is smaller than suggested by K13a who estimated an enhancement of a factor of 2, but consistent with a forthcoming study that has repeated this analysis on much larger sample of galaxies (Lofthouse et al., in prep). Interestingly, the star formation enhancement in major mergers shows a gradual increase with decreasing redshift. This is likely driven by the gradual decrease in the ‘background’ level of star formation in normal (non-merging) galaxies, as has been noted in recent observational work (e.g. K13a). In other words, as star formation activity in galaxies becomes progressively more quiescent, the impact of a major merger becomes proportionately higher. Indeed in the local Universe, where star formation driven by secular processes is significantly weaker than at high redshift (e.g. Pannella et al. 2014), gas-rich major mergers can enhance star formation by orders of magnitude (e.g. Mihos & Hernquist 1996), in contrast with the situation at $z > 1$.

Taken together with the relatively low frequency of major mergers (recall that only $\sim 30\%$ of massive galaxies at $z \sim 1$ have had such a merger), this indicates that, overall, the major merger process is not a significant driver of stellar mass growth at these redshifts. In Fig. 5, we quantify this further by calculating the fraction of the star formation budget that is hosted by major and minor mergers ($R < 10 : 1$). This fraction is around 25% across our redshift range of interest. Around two-thirds of this value (17%) is in systems with $R < 4 : 1$ (i.e. major mergers), again slightly lower than the observational estimate of Kaviraj et al. (2013a) but consistent within the observational uncertainties.

5 SUMMARY

We have used Horizon-AGN, a hydrodynamical cosmological simulation that reproduces the mass functions and rest-frame UV-optical colours of massive galaxies at $z > 1$, to probe the merger histories of massive galaxies and the impact of merging (major mergers in particular) in triggering

stellar mass growth at $1 < z < 4$. Our main conclusions are as follows:

- The fraction of massive galaxies in major mergers ($R < 4 : 1$) is around 3%, while the fraction of systems in major or minor ($R < 10 : 1$) mergers is around 11%. The merger fractions show no trend with redshift in the range $1 < z < 4$.

- Minor mergers ($4 : 1 < R < 10 : 1$) are around a factor of 2.5 more frequent than their major counterparts at $1 < z < 4$.

- At $z \sim 1$, $\sim 30\%$ of massive galaxies have undergone a major merger, while all massive galaxies have undergone either a major or minor merger, i.e. a merger with $R < 10 : 1$.

- While almost all major mergers at $z > 3$ are blue (i.e. result in significant star formation), the proportion of red mergers increases at $z < 2$, with most major mergers at $z \sim 1.5$, producing remnants that are red in rest-frame UV-optical colours.

- The enhancement of star formation in major mergers at these epochs is relatively mild ($\sim 20\text{--}40\%$). Together with the low frequency of these events, this indicates that major mergers are not significant drivers of stellar mass growth at these redshifts.

- (Only) a quarter of the total star formation budget is hosted by mergers with $R < 10 : 1$. While they are a key feature of the standard hierarchical paradigm, mergers with $R < 10 : 1$ play a relatively insignificant role in driving stellar mass growth in the early Universe.

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